Splices, Connectors, and Fiber Optic Components

- Fiber cable lengths are limited
- How do we join fibers?
  - Splices
  - Connectors
- Can we divide the power in a fiber?
  - Ex., 1 fiber in; 2 fibers out
- How can we isolate a laser source from back reflections?
- Can we make optical filters out of fibers (i.e., ready to splice into fiber links)?

Fiber Joints

- **Joints**
  - **Interconnect fiber lengths**
    - **Available up to few kilometers**
  - **Connect source/detector pigtails to fiber**
  - **Pass through bulkheads, walls, etc.**
- **Want...**
  - **Low insertion loss**
  - **High strength**
  - **Simple installation**
- **Two types of joints**
  - ***Splice*: permanent joint**
  - ***Connector*: temporary joint**

Connectors and Splices: Joining Losses

- **Causes of loss**
  - ***Intrinsic losses:*** **Depend on fiber properties**
  - ***Extrinsic losses:*** **Losses due to external factors (e.g., fiber misalignment)**
- **Coupling efficiency:**

$$\eta = P_{\text{out}} / P_{\text{in}}$$

  - **In general, <u>not</u> same in both directions**
- ***Joint loss:*** **dB equivalent of coupling efficiency**

$$L_j = -10 \log\left(P_{\text{out}} / P_{\text{in}}\right) = -10 \log(\eta)$$

Splice-3

Fiber Parameter Effects: Multimode Fibers

- **Coupled optical power depends on number of modes in each fiber**
  - **Number of modes:**

$$N = k^2 \int_0^a \mathrm{NA}^2(r)\, r\, dr = k^2 \mathrm{NA}^2(0) \int_0^a \left[1 - (r/a)^g\right] r\, dr$$

  - **Optimum coupling when number of modes is matched**
  - **Loss factors**
    - » **Core radius *a, n*umerical aperture NA(0), index gradient *g***
  - **Isolate effects as if independent and add dB losses**
- **Losses also depend on mode *power distribution***
  - **Assume uniform distribution**
  - **Reality: uneven distribution due to launch conditions or mode coupling effects**
  - **Measurements need to be made with all modes equally excited**

Fiber Parameter Effects: Multimode Fibers (cont.)

- **Effects of joining mismatched fibers**

1. NA effects:

$$\eta_{NA} = \begin{cases} \left(\dfrac{NA_r(0)}{NA_e(0)}\right)^2 & NA_r(0) < NA_e(0) \\ 1 & NA_r(0) > NA_e(0) \end{cases}$$

$$\Rightarrow L_{NA}[dB] = -10\log(\eta_{NA})$$

$NA_r(0)$ [$NA_e(0)$] is NA of receiving [emitting] fiber

2. Fiber radius effects:

$$\eta_r = \begin{cases} \left(\dfrac{a_r}{a_e}\right)^2 & a_r < a_e \\ 1 & a_r > a_e \end{cases}$$

$$\Rightarrow L_r[dB] = -10\log(\eta_r)$$

3. Index profile effects:

$$\eta_g = \begin{cases} \dfrac{g_r(g_e+2)}{g_e(g_r+2)} & g_r < g_e \\ 1 & g_r > g_e \end{cases}$$

$$\Rightarrow L_g[dB] = -10\log(\eta_g)$$

Combined effects:

$$\boxed{L_{Total}(dB) = L_{NA} + L_r + L_g}$$

Splice-5

- E.g., Coupling 50/125 SI (emitting) fiber with NA of 0.15 to 62.5/125 GI (g = 2) receiving fiber with NA =0.20 gives η = 0.5 (3 dB)

Fiber Parameter Effects: Multimode Fibers (cont.)

- **Loss is also function of...**
  - **Quality control of fiber fabrication**
    - » **Ellipticity of core**
    - » **Variations in *n(r)***
    - » **Core concentricity within cladding**
    - » **Variation in core diameter**
    - » **Other factors that depend on fabrication tolerances**
  - **Dominant effects: core diameter and NA**
  - **Lesser effect: core ellipticity and *n(r)***
- **User has little control over these factors**
  - **Specify tolerances**
  - **Establish acceptance screening procedures**

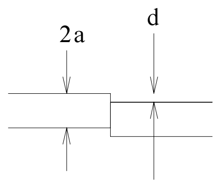
Splice-6

Splices and Connectors: Misalignment Effects

- ***Extrinsic* effects**
  - **Under control of connector/splice designer and user**
- **Primarily due to misalignment of fibers**
- **Determine required mechanical tolerances to meet given loss allocation**
- **In analysis of misalignments, usual assumptions are…**
  - **Fibers have equal radii, index profiles, and NAs to isolate misalignment effects**
  - **Power is uniform distribution across core area**

Connectors and Splices: Lateral Displacement Effects

- **Losses due to lateral fiber offset**



SI fiber:

$$\eta_{\text{SI lateral}} = \frac{2}{\pi}\cos^{-1}\left(\frac{d}{2a}\right) - \frac{d}{\pi a}\sqrt{1-\left(\frac{d}{2a}\right)^2}$$

$$\Rightarrow \quad L_{\text{SI lateral}} = -10\log\left(\eta_{\text{SI lateral}}\right)$$

(Calculation of overlapping circular areas, centers separated by *d*)

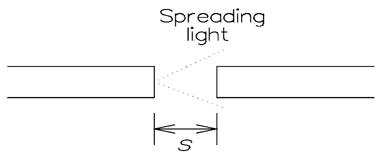
- **GI fiber:**

$$\eta_{\text{GI latral}} \approx 1 - \frac{8d}{3\pi a} \quad \text{or} \quad \eta_{\text{GI lateral}} \approx 1 - \left(\frac{2d}{\pi a}\right)\left(\frac{g+2}{g+1}\right)$$

$$\Rightarrow L_{\text{GI lateral}} = -10\log\left(\eta_{\text{GI lateral}}\right)$$

Connectors and Splices: Longitudinal Displacement Effects

- Losses due to **longitudinal displacement**



- Some light has spread beyond the area of receiving fiber core

- SI fiber:

$$\eta_{\text{SI long}} = \left(\frac{1}{1 + \frac{s}{a}\tan\theta_{\max}} \right)^2 \Rightarrow L_{\text{SI long}} = -10\log\left(\eta_{\text{SI long}}\right)$$

(θ_{max}: maximum acceptance angle = $\sin^{-1}$ NA)

Or

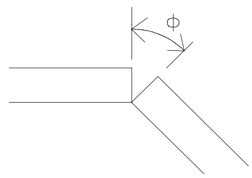
$$\eta_{\text{SI long}} \approx 1 - \frac{s\sqrt{2\Delta}}{4a} \Rightarrow L_{\text{SI long}} = -10\log\left(\eta_{\text{SI long}}\right)$$

- GI fiber: No similar formula available (?)

Splice-9

Connectors and Splices: Angular Misalignment

• **Losses due to angular misalignment**



GI and SI fiber:

$$\eta_{\text{angular}} \approx \frac{1}{1+\dfrac{\sin\phi}{\sqrt{2\pi\Delta}}\left(\dfrac{\Gamma\left(\dfrac{2}{g}+2\right)}{\Gamma\left(\dfrac{2}{g}+\dfrac{3}{2}\right)}\right)} \quad \Rightarrow \quad L_{\text{angular}} = -10\log\left(\eta_{\text{angular}}\right)$$

Γ(x) is Gamma function

Splice-10

Splices and Connectors: Reflection Losses

- *(Fresnel) reflection* **loss**
  - Coupling efficiency at perpendicular interface is

$$\eta_{\text{reflection}} = \frac{P_{\text{transmitted}}}{P_{\text{incident}}} = 1 - \left(\frac{n - n_0}{n + n_0}\right)^2 \quad \Rightarrow \quad L_{\text{reflection}} = -10\log(\eta_{\text{reflection}})$$

  - Reflection losses same regardless of direction of travel
  - Losses at air-glass interface: 0.2 dB each fiber face
  - Eliminate by…
    - » Use of index-matching gel or epoxy between fiber ends
    - » Physical contact of fiber ends ("PC" connection)
    - » Angled fiber ends
    - » Using optical isolators
- **Return loss**

$$L_{\text{return}} = -10\log\left(\frac{P_{\text{reflected}}}{P_{\text{incident}}}\right)$$

Total Losses in MM Fiber

- **Total loss in multimode fiber is sum of all losses...**

$$L_{\text{intrinsic}} = L_{\text{NA}} + L_{\text{r}} + L_{\text{g}}$$

$$L_{\text{extrinsic}} = L_{\text{lateral}} + L_{\text{logitudinal}} + L_{\text{angular}}$$

$$\boxed{\begin{aligned} L_{\text{MM Total}} &= L_{\text{intrinsic}} + L_{\text{extrinsic}} + L_{\text{reflection}} \\ &= L_{\text{NA}} + L_{\text{r}} + L_{\text{g}} + L_{\text{lateral}} + L_{\text{logitudinal}} + L_{\text{angular}} + L_{\text{reflection}} \end{aligned}}$$

Splice-12

Connectors and Splices: Single-Mode Fibers

- **Mode field diameter (MFD) determines sensitivity to misalignment**
- **Coupling efficiency for two single-mode fibers**
  - **MFDs of W_e (emitting fiber) and W_r (receiving fiber)**
  - **Lateral offset *d*, longitudinal offset *s*, and angular misalignment θ**

$$\boxed{L_{\text{Total SM}} = -10\log\left(\frac{16 n_1^2 n_3^2}{(n_1+n_3)^2}\frac{4\sigma}{q}e^{-\frac{\rho u}{q}}\right)}$$

n_1 is refractive index of fiber cores **(same for both fibers)**

n_3 is refractive index of medium between fibers

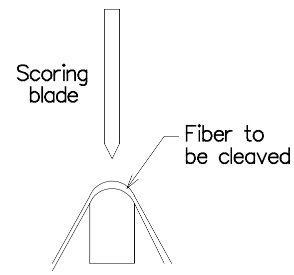
$$\sigma = \left(\frac{W_2}{W_1}\right)^2, \quad k = \frac{2\pi n_3}{l}, \quad \rho = (\mathrm{k}\mathrm{W}_1)^2,$$

$$F = \frac{d}{kW_1^2}, \quad G = \frac{s}{kW_1^2}, \quad q = G^2 + (\sigma+1)^2, \text{ and}$$

$$\mathrm{u} = (\sigma+1)F^2 + 2\sigma FG\sin\theta + \sigma\left(G^2+\sigma+1\right)\sin^2\theta$$

Splices and Connectors: Fiber End Preparation

- **Pits or imperfections scatter light**
- **End preparation techniques**
  1. ***Grinding and polishing technique***
     - » **Polish fiber end by hand or machine**
     - » **Uses progressively finer abrasives**
     - » **Labor and time-intensive**
  2. ***Score-and-break technique***
     - » **Fiber under mild tension and scribed**



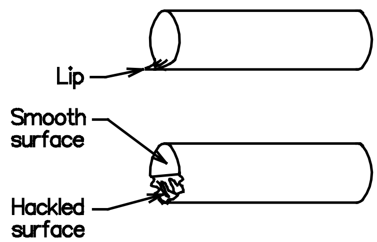
     - » **Tension increased and crack tip propagates across fiber**
     - » **If fiber curvature and tension are carefully controlled,**
       - **Crack propagates perpendicular to fiber axis**
       - **Creates clean, smooth break**

Splice-14

- Expressions for coupling loss all assume that fiber end is perfect transmitter
- End faces should be parallel to each other (often perpendicular to fiber axis)

Splices and Connectors: Fiber End Preparation (cont.)

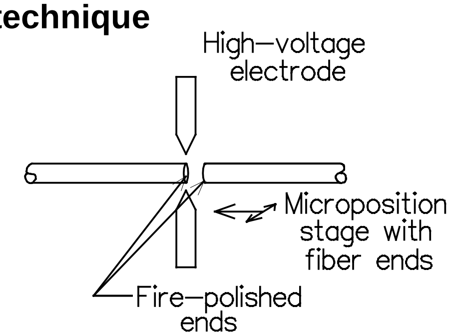
- Improper surfaces can have *lip* or *hackle*



- Microscope inspection of fiber end necessary for end inspection
- Tools commercially available
- Takes little time for experienced user

Splices: 1. Fusion Splicing

- **Most popular splice technique**



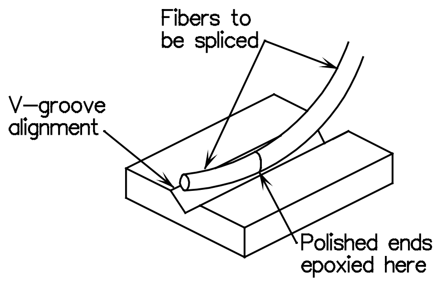
  - **Micro-manipulators bring prepared ends into close alignment (can be automated)**
  - **Ends heated with electric arc until molten; pushed together**
  - **Joint cools, surface tension pulls fibers into alignment**
- **Losses: ~ few tenths of a dB**
- **Primary problem**
  - **Reduced fiber strength near joint (about 60%of initial strength)**
    - **Use high-strength wrapping around spliced region**

Splice-16

- Strength reduction due to
  - ✳ Development of surface microcracks during handling and
  - ✳ Chemical changes in glass due to heating

Splices: 2. V-groove splice

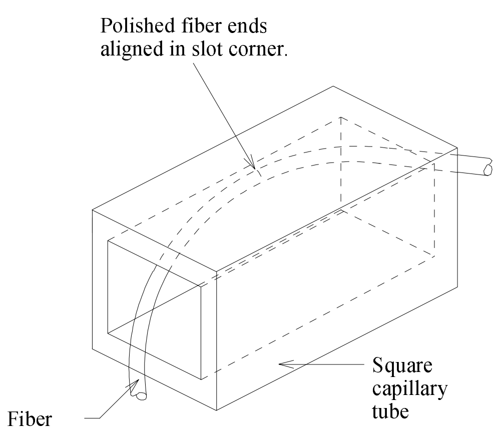
- V-shaped groove as alignment aid: mechanical alignment
- Apply epoxy or cover plate



- Grooves in plastic, silicon, ceramic, or metals
- Uses outside surface of fiber as reference
  - Susceptible to variations in core ellipticity, concentricity, and size
  - Unequal diameters cannot be spliced
- Fiber ends require preparation before splicing
- Losses: few tenths of a dB

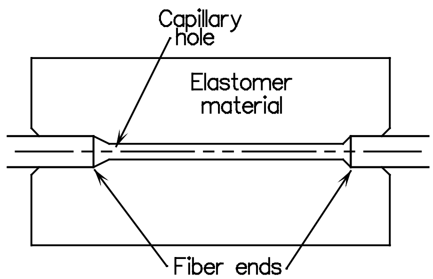
Splice-17

- Variation on this technique, called *loose-tube splice*, uses corner of a rectangular tube as the alignment aid



Splices: 3. Elastic Material Splicing

- Uses elastic material to center fibers



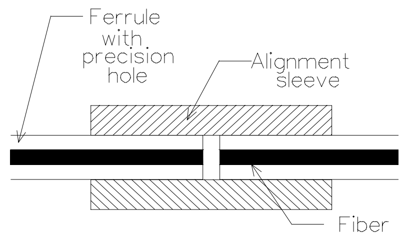
- Self-centering
  - Restoring forces center fiber (with respect to outside surface)
  - Unequal diameters can be aligned
- Fiber ends prepared before insertion
- Drop of epoxy on fiber ends forms splice
- Losses: few tenths of a dB

Connectors

- Allow disconnection and reconnection
- Goal: low insertion-loss connector with reproducible losses
- Most connector designs incorporate fiber into precision alignment aid
  - Aid then plugs into receptacle in connecting piece
- Various environmental factors:
  - Dust levels
  - Pressure differentials
  - Water vapor and water

Connectors: Ferrule-Based Connectors

- ***Ferrule***: precision-drilled hole in cylinder (fiber fits inside hole)
- **Ferrule fits in *alignment sleeve* to bring the fiber ends into alignment**

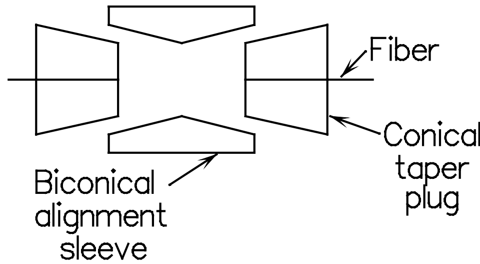


- **Main problems:**
  - **Centering fiber hole in ferrule**
  - **Dimensional tolerance on ferrule hole (e.g., 126±1 μm)**
  - **Centering ferrule hole in alignment sleeve**
  - **Making hole slightly larger than fiber**
- **Alignment sleeves commonly made of aluminum, stainless steel, or ceramics**

Splice-20

Connectors: Biconic Plug

- Injection-mold alignment element

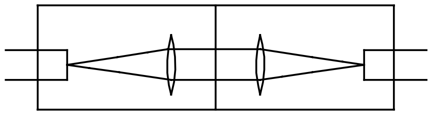


- Shape is “biconical taper”
- Designed to mate with housing such that fiber/plug assembly is self-centering
- AT&T patented
- Seldom used in new installations

Splice-21

Connectors: Expanded Beam Connector

- **Microlens inserted at fiber end to *collimate* beam**
  - **Expanded beam has less beam divergence**



- **Receiving fiber has similar collimator**
- **Expanded beam reduces requirements on lateral & longitudinal alignments**
  - **Penalty of increasing required angular alignment**
- **Lenses:**
  - **Microlens**
  - **Gradient-index lenses**
  - **Mounted into alignment fixture**
- **Fiber ends prepared prior to insertion**
- **Losses: few tenths of a dB**

- Gradient-index lens
  - ☞ Piece of glass with parabolic variation in *n(r)*
  - ☞ Behaves as a lens but has flat surfaces
  - ☞ Also called *GRIN lens*

Connectors: Commercial Connectors

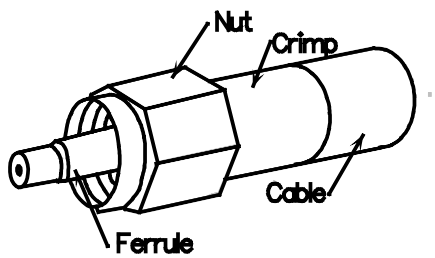
- Several connector popular types
- Few standards for connectors
- Patent and proprietary rights
  - Frequently “second-sourced" or cross-licensed
- Typical insertion losses for connectors in the field
  - Few tenths of a dB to a few dB

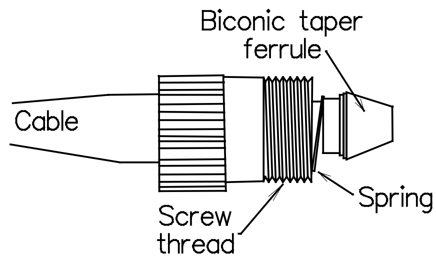
Splice-23

Commercial Connectors: SMA & Biconic Connectors

- **SMA connector (left)**
  - **Borrowed from RF field**
  - **Formerly popular connector for multimode fibers**
  - **Ferrule-type connector**

- **Biconic connector (right)**
  - **Developed by AT&T**
  - **Wide use in older single-mode systems**
  - **Supplanted by ST connector**
  - **Uses molded and ground plastic or ceramic plug**

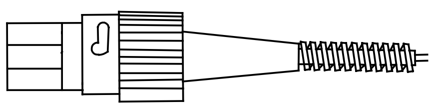




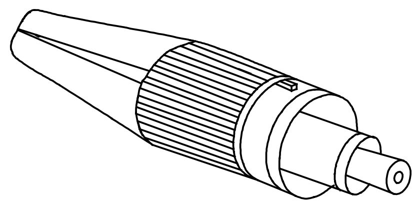
Splice-24

Commercial Connectors: ST & FC Connectors

- **ST connector (left)**
  - Registered trade-mark (AT&T)
  - Widely used in single-mode systems
  - Also available for multimode systems
  - Features spring-loaded bayonet clip
  - Both score-and-break and grind-and-polish methods used to prepare fiber ends
  - Fairly easy to terminate



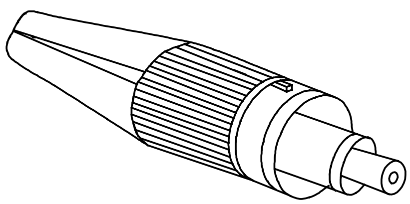
- **FC connector (right)**
  - Developed by NTT (Nippon Telephone and Telegraph)
  - Single-mode fibers
  - *D3 connector* is NEC (Nippon Electronics Corporation) clone of FC connector
  - Spring-loaded connector with screw-on nut
  - Metal ferrule aligns fiber



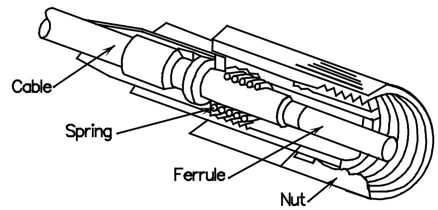
Splice-25

Commercial Connectors: FC/PC & D4 Connectors

- FC/PC connector
  - Offshoot of FC connector
  - Pure ceramic ferrule
    - » Increased alignment accuracy over metal/ceramic ferrule in FC
  - Physical contact to minimize reflections
  - Primarily used for long-haul and research instruments



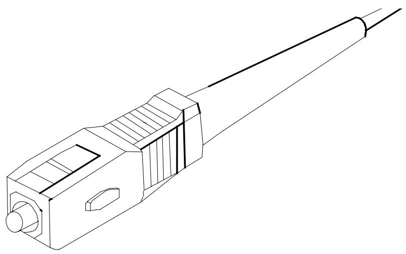
- D4 connector
  - Designed by NEC
  - Similar to D3 connector, but smaller

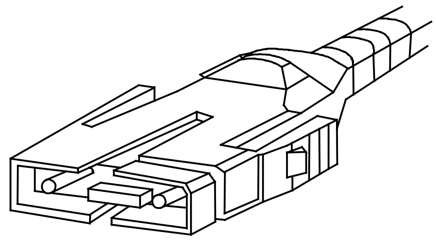


Splice-26

Commercial Connectors: FDDI Connectors

- **SC connector**
  - Plastic-case connector
  - Push-pull configuration
  - Ceramic ferrule
  - Increasingly popular in networks
- **FDDI connector**
  - Dual-fiber connector
  - FDDI standard
  - Use in FDDI data links
  - Used for attachment to stations on link

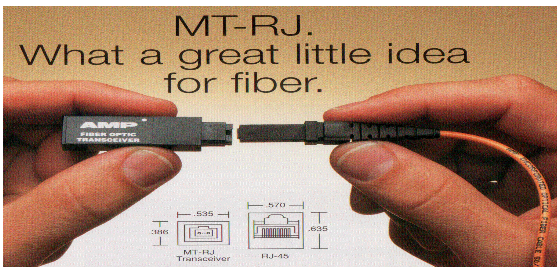


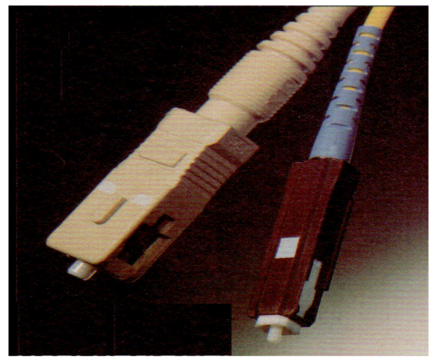


Splice-27

Miniature RJ and MU Connectors

- New connectors
- Network applications
- Compatible with network wall plugs
- Small “footprint”
- RJ (left)
- SC vs MU (right)





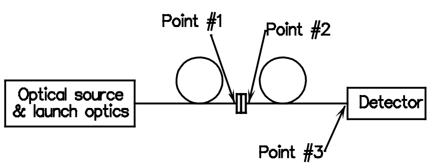
Splice-28

ST-Connector Spec Sheets

- **See course Web site**

Splice and Connector: Loss Measurement

- **Measured losses depend on many variables**
  - **Optical power launch conditions**
    - **Excite all modes in MM fiber**
      - **Use long pigtail**
      - **Equilibrium mode simulator: short fiber wrapped in serpentine path**
  - **Source type**
  - **Characteristics of fiber on either side of joint**
- **Experimental setup**
  - **Measure power P_1 and P_2 at the input and output of connector**



$$L_{\text{splice}} = -10\log\left(P_2 / P_1\right)$$

insertion loss

- Losses measured are very susceptible to mode excitation
  - ☞ Equal mode excitation desired
  - ☞ Can use
    - ✳ Long fiber before connector/splice
    - ✳ Shorter fiber wrapped in serpentine path
- Multimode fibers can introduce loss effects
  - ☞ Due to mode coupling and connector/splice effects

Couplers

- Couplers
  - Split power into two or more fibers
  - Combine optical power
  - Split light according to polarization
  - Optical switches: switch light between output fibers
- Usually each output equally shares signal
  - Possible to vary *coupling fraction*
- Losses
  - *Splitting loss*: $L_{\text{pwr split}} = -10\log(1/N) = 10\log(N)$
  - *Excess losses:* extra losses
  - *Insertion loss:* Splitting loss plus insertion loss
  - Splitting matrix:

Losses		Output port	
		A	B
Input port	1	3.5 dB	3.5 dB
	2	3.5 dB	3,5 dB

Splice-31

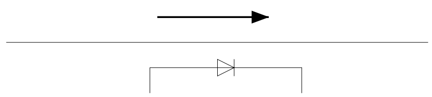
Coupler Functions

- ***Splitter*** **(left)**
  - **Splits/divides power**
  - **Standard splits for 2x2: 50:50, 90:10, 99:1**
  - **Other custom ratios**
- ***Polarizing splitter***
  - **Splits signals into two outputs**
  - **Output polarizations orthogonal**
  - **Single-mode fibers**
- ***Combiner*** **(right)**
  - **Combines input channels into one**
  - **Coherent combination possible with SM fiber**
  - **Many (*not* all) passive devices are reciprocal**
    - » **Splitter sometimes used as combiner**

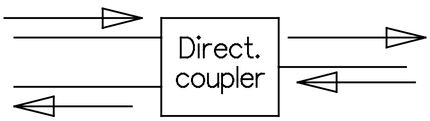
Splice-32

Coupler Functions (cont.)

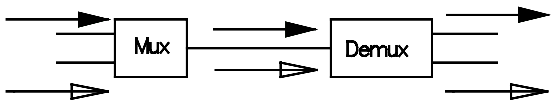
- ***Monitor***:
  - Couples little light (e.g., 1%) into monitor port



- ***Directional coupler*** (or *circulator*) :
  - Nonreciprocal device
  - Isolates one input from one output

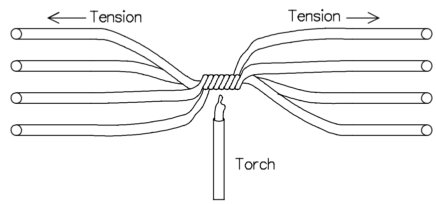


- **Multiplexer** (wavelength multiplexer):
  - Combiner
  - Joins two or more signals at different wavelengths
- **Demultiplexer** (wavelength demultiplexer):
  - Splits signals according to wavelength



Couplers: 1. Fused Coupler

- **Also called *biconical taper coupler***
- **Light couples into other fibers through thinned cladding**
  - ***Evanescent wave coupling***

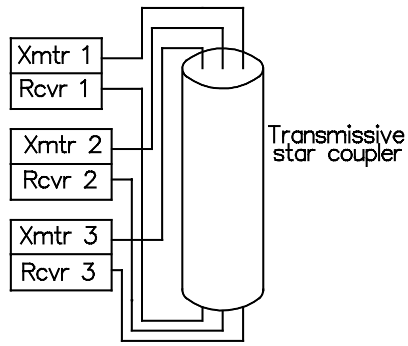


- **Coupling fraction controlled by amount of tension and time of heating.**
  - **Surprisingly, equal coupling can be achieved for all fibers with very low crosstalk and low insertion loss**
  - **>100 fibers formed into star coupler**

Splice-34

Couplers: 2. Mode-Mixing Rods

- Glass rod
  - Few mm diameter
  - Graded-index profile
  - Length allows input light to fully expand
  - Output end uniformly excited
- Concept works in transmissive configuration
  - Make *reflective* system by
    - » Cutting in half,
    - » Adding reflecting surface,
    - » Moving outputs to same end as inputs



Splice-35

Couplers: Typical Specifications

- Losses
  - Desired *splitting loss*
    - » $L_{split} = -10\log(1/N) = \log N$ dB
  - Undesired *excess loss*
    - »Typical excess losses: ~ 0.5 dB
- SM and MM couplers available
- See course web site for sample spec sheet

Splice-36

Splices, Connectors and Couplers: Summary

- Splices and connectors
  - Losses depend on...
    - » **Fiber geometry** (core ellipticity, core-cladding concentricity, area mismatches, etc.)
    - » **Characteristics of fiber** (NA, index profile)
    - » **Mechanical alignment** (lateral and longi-tudinal displacement, angular misalignment)
    - » **Power distribution in fiber** (excitation conditions or mode conversion effects)
    - » **Fiber end-face quality** (scratches, presence of lips or hackles, parallelness of end faces)
  - Commercial connectors and splicing have acceptable losses (<1 dB)

- Couplers
  - Combine and separate light
  - Primary parameters
    - » Excess insertion loss
    - » Splitting loss of coupler

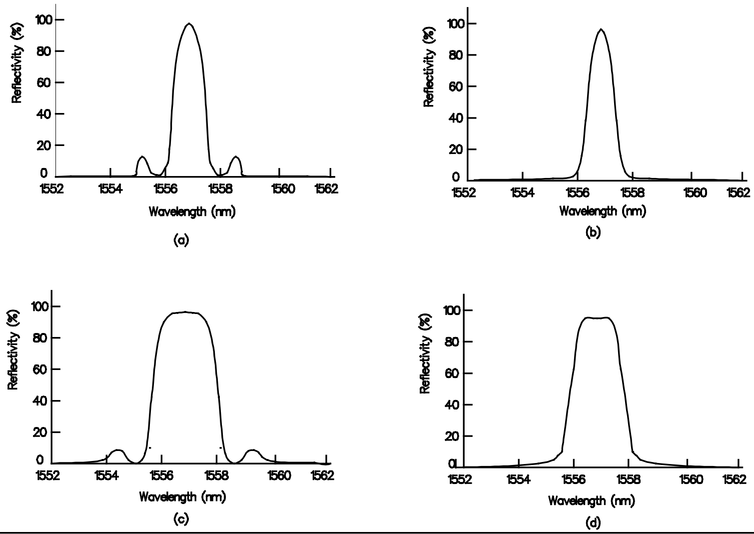
Splice-37

Fiber Grating Devices

- Goal: Inline optical filters with low insertion loss
- Applications
  - Add/drop filters for multiwavelength systems
  - Reflectors for amplifiers and fiber lasers
  - Reflectors for external-cavity lasers
  - Dispersion compensating devices
- Physical effect
  - High intensity UV can change *n* of glass (permanently)
  - Expose fiber to interference pattern to write "grating" in fiber core
    - » Use side exposure through "phase mask"
  - Transmission/reflection spectral properties depend on grating period and amplitude

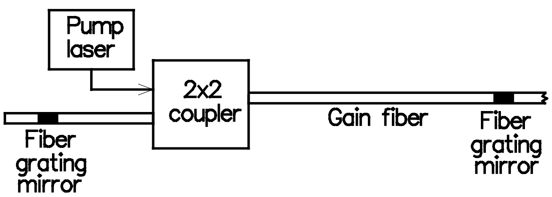
Grating Designs

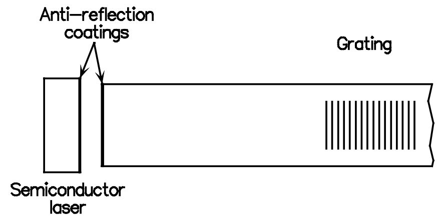
- Spectral distribution of reflectivity
  - (a) Period grating, equal amplitude
  - (b) Periodic grating, apodized amplitude
  - (c) "Chirped" period, equal amplitude
  - (d) Chirped period, apodized amplitude



Fiber Gratings: Laser Reflectors

- **High reflectivity at desired wavelength**
  - **Left - fiber laser with grating mirrors**
  - **Right - external cavity laser (long resonator length ensures small $\Delta\nu$)**

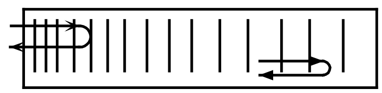




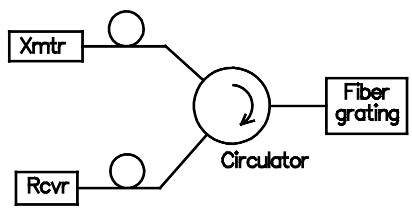
Splice-40

Fiber Gratings:Dispersion Compensation

- **Aperiodic grating**
- **Short-λ reflect in regions of high spatial periodicity**
- **Design grating to "reverse" pulse-stretching effects of GVD dispersion in SM fibers**



(a)



(b)

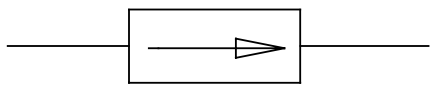
Splice-41

Fiber Grating Spec Sheet

- See course web site

Optical Isolators

- Ensure one-way light flow
- Return loss
  - –30 dB nominal
  - –60 dB premium device
- Applications
  - Isolate single-frequency lasers
  - Isolate optical amplifiers
- See course web site for sample spec sheet



Summary

- **Use splices for permanent connection; connectors for demountable connection**
  - **Losses depend on fiber properties** **(intrinsic losses)** **and fiber alignment** **(extrinsic losses)**
  - **Losses ~0.1s dB**

- **Fiber components**
  - **Splitters, combiners, circulators** **(directional couplers),** **multiplexers and demultiplexers, switches, polarization components** **(splitters, combiners, isolators)**
  - **Filters** **(Bragg gratings, stacked dielectric layers, Fabry-Perot mirrors)**